EFFECT OF DISTANCE ON AEROACOUSTIC WAVES FROM DOUBLE CAVITIES IN TANDEM ARRANGEMENTS

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Abstract. The change of the flow fields in three cases of double cavities in tandem arrangements is investigated using large eddy simulation (LES). This flow fields which Mach 0.6 flows over cavities with a length-to-depth ratio of L/D = 1 are investigated. The consequences on effect of distance between double cavities on noise generation are considered. In this study, three cases with different distance between first cavity and second cavity are investigated. The sixth-order compact difference scheme is adopted for the spatial difference. The sixth-order filter is employed. The filter coefficient is set to $\alpha = 0.44$. Second-order six-stage Runge-Kutta method is adopted as time integration. Four low-frequency peaks in a spectrum of sound pressure level are observed in the case of one cavity. These cavity modes show qualitative agreements with Rossiter's modes. These peaks are also observed in the cases of tandem cavities. In the backward cavity of the tandem cavities, the sound pressure levels in broadband without peak frequencies are increased. The knowledge of predicting the frequencies of discrete tones and the details of these physical processes are discussed.

1 INTRODUCTION

In the past, the aerodynamic noise from vehicle was smaller than a mechanical noise from the vehicle. However, because the reductions of a mechanical noise are being conducted, the aerodynamic noise is becoming larger relatively. In addition, considering the speed-up of transportations in recent years, it is expected that aerodynamic noise will become a main noise source in a high speed vehicle because it is increasing with sixth or eighth power of the vehicle speed. Especially, flow over a concave-convex shape can be a strong acoustic wave source because of flow-fluctuations generated by the shape. Therefore, it is important to understand aeroacoustic fields of a flow over a concave-convex shape concave-convex shape such as a bump or a cavity have been conducted.[1,2]

However, a multiple concave-convex shape is used for actual design of a vehicle, and a flow over such a shape seems to generate very complex aeroacoustic fields, in which a flow and acoustic waves are affected by multiple concaves or convexes. Therefore, it is necessary to investigate aeroacoustic fields of a flow over a multiple concave-convex shape, which have not been well-investigated.

In this study, a multiple concave-convex shape is simply modeled as double cavities in tandem arrangements, and characteristics of aeroacoustic fields of a flow over double cavities are investigated. It is well-known that a flow over a single cavity generates peaky tone noise, so-called cavity tone, because of an impinging self-oscillated shear layer. In a case of cavities in tandem arrangements, it is expected that disturbance generated by a front cavity affect a flow fields over a rear cavity, resulting in change in characteristics of aeroacoustic fields. Moreover, it is expected that interference of acoustic waves from two cavities affect the characteristics of aeroacoustic fields, where the interference of acoustic waves seem to depend on the distance of cavities.

In this paper, direct noise computation of a flow over double cavities in tandem arrangements is conducted and, effects of double cavities and their distance on the aeroacoustic fields are discussed.

2 COMPUTATIONAL SETTINGS

2.1 **Problem settings**

A schematic and notation of the flow domain is shown in Fig. 1. *L* is length of a cavity, *D* is depth of a cavity, *W* is a width of a cavity, and *H* is a distance between cavities. Cavity geometry is set to a cube (L=W=D) for simplicity. Sizes of a front cavity and a rear cavity are same. In this study, one case for a single cavity and three cases for double cavities with different distance *H* are simulated. A case for a single cavity is named 1Cavity. Distance *H* between cavities for tandem cavities are set to 0.5D, 1.0D and 2D for three cases. Cases for double cavities are named as 05D, 1D, 2D for cases with H=0.5D, 1.0D and 2.0D.

Freestream Mach number M is set to 0.6 for understanding mechanism of aeroacoustic waves from high speed vehicle. Reynolds based on the cavity depth D and freestream is set to 28,700. For inflow condition, laminar boundary layer profile solved with Blasius equation is adopted. Here, momentum thickness of the boundary layer is set to 0.03D at the origin point.



Figure1: Schematic of geometry and coordinate system

2.2 Computational method

Three-dimensional Navier-Stokes equations are used as the governing equations in this analysis to treat the sound wave from turbulent flow. It is necessary to use high-order scheme to resolve the turbulence and sound wave that is a slight pressure fluctuation. Spatial derivatives in convective terms, viscous term, and metrics and Jacobian are evaluated by the sixth-order compact difference scheme.[3] Near the boundary, the fourth-order explicit difference schemes are used. The sixth-order tri-diagonal filter applied with $\alpha = 0.45$ is used to remove the high frequency wave that makes calculation unstable.[4] To reproduce correct turbulent flow, direct numerical simulation (DNS) is most effective, but DNS needs too much calculation cost. Therefore, ILES is used in this research. In the standard LES approach, additional SGS stress and heat flux terms are appended, but in ILES approach they are not appended. Instead, a high-order lowpass filter is applied to the conservative variables. This filter selectively damps only the poorly resolved high-frequency waves. This filtering regularization procedure provides an attractive method to the use of standard sub-grid-scale (SGS) models. Optimized sixstage second order Runge-Kutta^[5] is used for time integration. This algorithm can use with a larger time step.

2.3 Computational grid

Figure 2 shows computational grid employed in this study. Here, Figs 2.a and 2.b present a *y*-constant plane and a *x*-constant plane, respectively. An enlarged figure inside Fig. 2 corresponds to a computational region, while buffer region by grid stretching[6] is employed around the computational region for avoiding nonphysical acoustic-wave reflection or generation. For inflow boundary, buffer region of 8D length is employed. A zonal grid system is adopted, and geometry of cavities is expressed with three zones. A zone 1 (black) grid is employed for outside region and zones 2 and 3 grids (red) are employed for inside a front cavity and a rear cavity, respectively. Total grid points are approximately 3 million as shown in Table 1.

2.4 Cut-off frequency

High and low cut-off frequencies are estimated from computational schemes, grids, and total time steps. A high cut-off frequency is estimated as St=2.0 using maximum grid spacing inside the computational region and acoustic-wave resolution of compact

scheme, whereas compact scheme is assumed to be able to resolve 8 point waves. A low cut-off frequency is estimated as St=0.33 which corresponds to 10th mode of Fourier analysis, whereas time steps and nondimensional duration for Fourier analysis are 50,000 and 50 respectively.

Table 1: Grid points of computational grids	. Grid points in stream	-wise, span-wise	, and normal-to-wall				
directions are presented							

	05Dcase		2Dcase	
Zone1 (outer region)	286 x 110 x 80	310 x 110 x 80	359 x 110 x 80	
Zone2 (front cavity)	50 x 50 x 55	50 x 50 x 55	50 x 50 x 55	
Zone3 (rear cavity)	50 x 50 x 55	50 x 50 x 55	50 x 50 x 55	



3 RESULTS AND DISCUSSIONS

Instantaneous pressure distributions for four cases are shown in Fig. 3. Acoustic waves observed in 1Cavity are similar to those observed in previous studies. In double



cavity cases, various acoustic waves are generated from front and rear cavities, resulting in complex aeroacoustic fields. In this section, these aeroacoustic fields are discussed.

Figure 3: Instantaneous pressure distributions

3.1 Peak frequencies of single cavity

SPL Spectra of single cavity is shown in Fig. 4. A measurement point of spectra is located at (x, y, z) = (0, 0, -0.33) in Fig. 1. For the purpose of validation of computation, peak frequencies in spectra of measurement point are compared with those of a semi-theoretical equation and a previous study. For a semi-theoretical equation, Rossiter's one is used. Here, Rossiter's equation[6] is written as follows:

$$f = \frac{U}{L} \frac{(n-\gamma)}{\left(\frac{1}{K} + M\right)} \qquad (n = 1, 2, 3 \cdots)$$
(1)

where γ is the phase-lag parameter and *K* is the ratio of disturbance convective velocity and freestream velocity. In this study, $\gamma=0.25$, *K*=0.57 are adopted. Nondimensional form of eq. (1) is

$$St = \frac{(n-\gamma)}{\left(\frac{1}{K}+M\right)} \qquad (n = 1, 2, 3 \cdots)$$
⁽²⁾

Table 2 shows peak frequencies of cavity tones of the present study, Rossiter's equation[6] and computational study of Gloerfelt et al.[7] Results of our computational

show qualitative agreements with those of Rossiter's equation and computational study of Gloerfelt et al. From the results, our computational results seem to be reliable enough for qualitative discussion of cavity tone noise.



St

Figure 4: Spectra of 1Cavity Table 2: Comparison of Stroubal number of peak frequency

	St1	St2	St3	St4	St5
1Cavity	0.33	0.63	0.96	1.3	1.66
Rossiter	0.32	0.74		1.17	1.59
	(n=1)	(n=2)		(n=3)	(n=4)
Gloefelt et. al.	0.32	0.66	0.903	1.25	1.55

3.2 Peak frequencies of double cavities

Comparison of spectrum of SPL for 1Cavity case with those of front cavity for double cavities case are shown in Fig. 5. Also, comparison of spectra of SPL for 1cavity case with those of front cavity for double cavities case are shown in Fig. 6.

Figure 5 shows that spectrum of front cavity for double cavities cases has the same trend as that of 1Cavity case, except that newly generated peaks are observed at $0.7 \sim 0.8$ in double cavities cases. These peaks seem to be generated by tandem arrangements. In the cases of 05D and 2D, peak levels at *St*=0.33, 0.63, and 0.96 do not change, and newly generated peaks has only 135dB level which is 25dB smaller than strongest peaks. On the other hand, in the case of 1D, peak level at *St*=0.96 is 7dB smaller than 1Cavity, and level of a newly generated peak is nearly 150dB. Except for the peaks, broadband characteristics of SPL do not change for all the cases.

Figure 6 shows that spectra of rear cavities have broadband increases in SPL except for the peak frequency. This seems to be due to turbulent noise generated by the turbulence generated by the front cavities. Peaks at St=0.63 are hidden by this turbulent noise. Peak levels at St=0.33 for the rear cavities are almost the same as those of 1Cavity case or front cavities. Peak level at St=0.96 of 05D is the same as the 1Cavity, while peaks at St=0.96 of 1D and 2D decrease with increasing distance. In these cases, newly generated peaks at $St=0.7\sim0.8$ are clearly observed instead. Especially, that of 1D case, which reaches 152dB, appears very clearly.



(c) 1Cavity & 2D case Figure 5: Comparison of spectra of front cavity



(c) 1Cavity & 2D case Figure 6 : Comparison of spectra of back cavity

3.3 Discussion on SPL distributions at *St*=0.33

In this subsection, SPL distributions at St=0.33 are discussed. SPL distributions at St=0.33 are shown in Fig. 7. Because SPL at St=0.33 inside cavity does not change at front and rear cavities, sound pressure level of double cavities cases appear to be estimated as the superposition of SPL in 1Cavity case. Here, SPL can be superposed by two different ways. One is the way assuming incoherent relation between acoustic waves from front and rear cavities. This assumption corresponds to that acoustic waves are generated from front and rear cavities independently. The other is the way assuming coherent relation between acoustic waves from front and rear cavities of SPL distributions of double cavities are in phase. Comparing computational results of SPL distributions of double cavities and estimated ones under different assumptions, relation between acoustic waves from front and rear cavities are discussed, and possibility of prediction of SPL distribution of double cavities based on results of the single cavity are clarified.

Figure 8 shows the phase of primary mode of disturbance in z-direction velocity along the wall at *St*=0.33. This phase is computed using short time Fourier and proper orthogonal decomposition used in References [8,9]. Based on the phase distribution, phase-lag at front and rear cavities is computed. Computed phase lags are $1/2 \pi$, $8/5 \pi$ and $3/5\pi$ for 05D, 1D and 2D, respectively. For the SPL estimation under assumption of coherent acoustic sources, these phase lags are used.

Figures 9-11 show the comparison of SPL of double cavities and estimated SPLs under two different assumptions, coherent acoustic wave generation and incoherent acoustic wave generation. From the results, estimated SPL under assumption of coherent acoustic wave sources shows good agreement with computed SPL. On the other hand, estimated SPL under assumption of incoherent acoustic wave source is different from computed SPL qualitatively. This shows that acoustic waves from double cavities are in phase, and prediction of SPL using single cavity results should be conducted with assumption of coherent acoustic wave generation.



Figure 7: SPL profile (St=0.33)



(c) 2D case Figure 8 : Phase distributions of primary mode of disturbance in z-direction velocity along the wall. A red line shows the geometry.







Figure 10: Comparison of computed SPL and estimated SPLs of 1D case at *St*=0.33. Estimation is based on the results of single cavity and assumptions of incoherent and coherent acoustic wave generation.



Figure 11: Comparison of computed SPL and estimated SPLs of 05D case at *St*=0.33. Estimation is based on the results of single cavity and assumptions of incoherent and coherent acoustic wave generation.

4 CONCLUSION

Flows over single cavity and double cavity in tandem arrangements with different distances are simulated, and aeroacoustic characteristics are discussed. From the results, characteristics of peaky tone noises are clarified as follows:

In the front cavity of all the double cavities cases, peaks at St=0.33, 0.63 and 0.96 are observed similar to the single cavity case. In addition, newly generated peaks around St=0.8 are observed for all the double cavities cases, which is clearly observed in the case of 1D.

In the rear cavity of all the double cavities cases, peaks at St=0.33 are observed similar to the single cavity case, while level of peaks at St=0.96 decreases with increasing distance between cavities. Despite of the decrease of peaks at St=0.96, newly generated peaks are also observed similar to the front cavities. Moreover, increased turbulent noise hide small peaks such as peaks at St=0.63.

Sound pressure level at St=0.33 of double cavities cases can be estimated using that of single cavities and coherent aeroacoustic wave generation. This shows that aeroacoustic wave sources have strong relation between each other at this frequency.

Additionally, characteristics of turbulent noise are clarified as follows:

In the rear cavity, turbulent noises are increased because of turbulent disturbance generated by the front cavity.

This characteristic of turbulent noise will be further investigated.

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