

CONTROL OF CAVITY TONE BY SPANWISE ALIGNED JETS IN UPSTREAM BOUNDARY LAYER

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INTRODUCTION

Self-sustained oscillations (with fluid-acoustic interactions) in a flow over a cavity often radiate intense tonal sound. In the development of many flow-related industrial products, it is important to predict these oscillations during the design stage and invent ways to suppress them.

Many researchers over the past 50 years have investigated the mechanism of the self-sustained oscillations in the cavity flows. Rossiter [1] described an oscillation mechanism similar to that presented for edge tones by Powell [2]. In this mechanism, the interactions of vortices with the downstream edge of the cavity radiate acoustic waves, which lead to the formation of new vortices at the upstream edge.

Zhuang *et al.* [3] researched the control of cavity tone by blowing at upstream edge of cavity. Huang *et al.* [4] succeeded in reduction of cavity tone using jets by spanwise aligned plasma actuators, which induce streamwise longitudinal vortices in the upstream boundary layer. However, the reduction mechanism and optimal spanwise pitch of the induced streamwise longitudinal vortices in reduction of cavity tone has not been clarified. The objective of this paper is to clarify the effects of spanwise aligned streamwise longitudinal vortices on the cavity tone. In this paper, longitudinal vortices are induced by spanwise aligned jets.

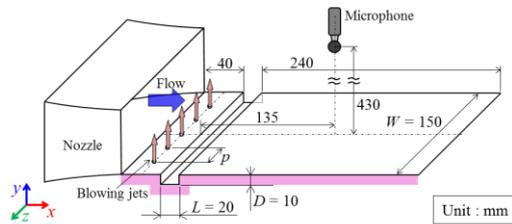


Figure 1: Experimental setup.

EXPERIMENTAL AND COMPUTATIONAL METHODS

Experiments were conducted using a suction-type low-noise wind tunnel shown in figure 1. The distance between the exit of the nozzle and the upstream edge of the cavity is 40 mm. The origin of the coordinate is at the position of the upstream edge of the cavity. In the spanwise direction, the cavity is terminated by two porous end walls to suppress the reflections of the sound. The background noise level is suppressed to less than 58 dB (A) at a wind speed of 30 m/sec.

The length and depth of cavity are constant at $L = 20$ mm and $D = 10$ mm. The control effects of the spanwise aligned

vertical jets in the upstream boundary layer on the cavity tone were investigated. Moreover, the spanwise pitch of jet was changed at $p/L = 0.1, 0.25, 0.6,$ and 1.25 . The freestream velocity was changed from 10 m/s to 45 m/s, and the jet velocity at the central axis of jet was also changed from $U_j = 2.2 - 4.0$ m/s.

We also simulate both flow and acoustic fields by directly solving the three-dimensional compressible Navier-Stokes equations in a conservative form, which are written as:

$$\mathbf{Q}_t + (\mathbf{E} - \mathbf{E}_v)_x + (\mathbf{F} - \mathbf{F}_v)_y + (\mathbf{G} - \mathbf{G}_v)_z = 0 \quad (1)$$

where \mathbf{Q} is the vector of the conservative variables, \mathbf{E} , \mathbf{F} , and \mathbf{G} are the inviscid fluxes, and \mathbf{E}_v , \mathbf{F}_v , and \mathbf{G}_v are the viscous fluxes. The spatial derivatives were evaluated by the sixth-order-accurate compact finite difference scheme (fourth-order accurate on the boundaries) [5]. Time integration was performed by the third-order accurate Runge-Kutta method.

Computations were performed at $U_0 = 43$ m/s without control and with jets of $U_j = 2.2$ m/s at 2 pitches of $p/L = 0.1, 0.25$. The Reynolds number based on cavity length and the freestream velocity is 5.7×10^4 . The origin of the boundary layer in the computation was adjusted so that the predicted velocity profile agrees with measured that. Figure 2(a) shows the measured and predicted averaged velocity profiles on a flat plate at a position corresponding to the leading edge of the cavity. The upstream boundary layer is laminar, and the boundary layer thickness is $\delta_{99\%}/L = 0.06$.

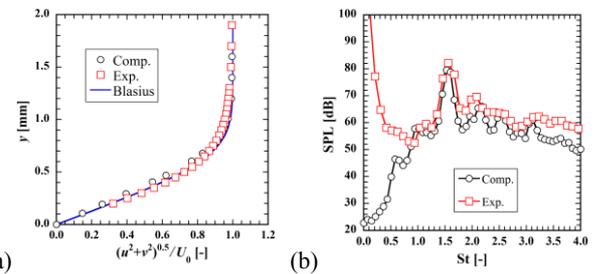


Figure 2: (a) Predicted and measured velocity profiles at position corresponding to upstream edge of cavity. (b) Predicted and measured sound pressure spectra at the freestream velocity of $U_0 = 43$ m/s without control ($x/L = 6.75, y/L = 21.5$).

Figure 2(b) shows the predicted and measured sound pressure spectra without control. As shown in this figure, the predicted peak level and frequency of tonal at the

nondimensional frequency of $St \equiv fL/U_0 = 1.5$ are in good agreement with measured those. Therefore, it has been concluded that the present computation correctly capture flow and acoustic fields in the cavity flows.

RESULTS

Figure 3(a) shows the measured sound pressure spectra under control with jets of $p/L = 0.1, 0.25, 0.6,$ and 1.25 compared with that without control at the freestream velocity of $U_0 = 37$ m/s. While the tonal sound still remains at the pitches of $p/L = 0.6$ and 1.25 , the tonal sound is apparently extinguished at the pitch of $p/L = 0.25$. Also, at the pitch of $p/L = 0.1$, the tonal sound still remains while the frequency of tonal sound is changed from $St = 1.6$ to 1.2 , where the mode related with number of vortices in the cavity is changed from the 3rd to 2nd.

Figure 3 (b) shows the influence of the freestream velocity on the difference of pressure level of tonal sound with and without control, ΔSPL . It is clarified that the sound pressure level is sharply reduced at the pitch of $p/L = 0.25$ particularly at higher velocity than 25 m/s.

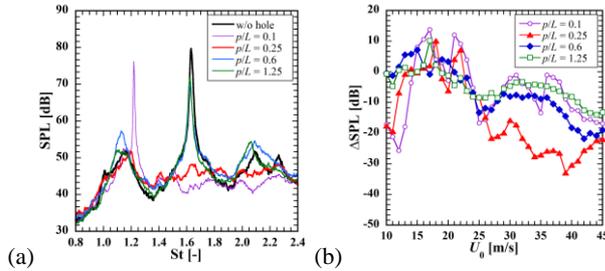


Figure 3: Control effects of jets of velocity of $U_j = 2.2$ m/s, and $p/L = 0.1, 0.25, 0.6, 1.25$ (a) Sound pressure spectra without control and with control at the freestream velocity of $U_0 = 37$ m/s. (b) Influence of freestream velocity on control effects.

Figure 4 shows the predicted iso-surfaces of the streamwise vorticity with jets of $p/L = 0.1$ and 0.25 . At the pitch of $p/L = 0.25$, the longitudinal vortices are induced in the upstream boundary layer, while intense vortices do not be induced at the pitch of $p/L = 0.1$. At the pitch of 0.25 , the longitudinal vortices are induced due to the spanwise variation of velocity in the downstream of exits of jets. At the pitch of 0.1 , the pitch is possibly too narrow to induce longitudinal vortices.

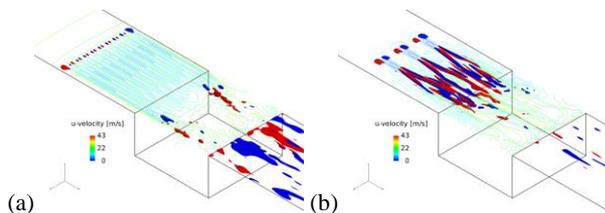


Figure 4: Iso-surfaces of streamwise vorticity of $\omega_x/(U_0/L) = 7$ (red) and -7 (blue), and contours of streamwise velocity U ($y/d = 0.16$) for averaged flow fields. (a) Flow field with $p/L = 0.1$. (b) Flow field with $p/L = 0.25$.

Figure 5 shows the iso-surfaces of second invariant with and without control. In the cavity flows without control, the two-dimensional large-scale vortices are shed and acoustic waves are radiated due to the collision of the vortices on the downstream wall. However, under the control of jets of $p/L = 0.25$, the above-mentioned longitudinal vortices inhibit the development of the two-dimensional vortices in the cavity flow. Figure 5(b) shows the two-dimensional vortices are not shed in the cavity flow with jets of $p/L = 0.25$. Because of the inhibition of two-dimensional vortices, the level of radiating sound is reduced at the pitch of $p/L = 0.25$. At the pitch of $p/L = 0.6, 1.25$, the pitch is too wide to inhibit the shedding of two-dimensional vortices. At the pitch of $p/L = 0.1$, the pitch is too narrow to induce the longitudinal vortices in the upstream boundary layer. As a result, the most intense sound reduction was achieved at the pitch of $p/L = 0.25$.

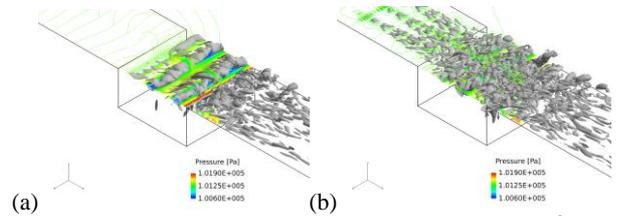


Figure 5: Iso-surfaces of second invariant of $Q/(U_0/L)^2 = 22$ and contours of p . (a) Flow field without control. (b) Flow field with jets of $p/L = 0.25$.

CONCLUSION

Regarding control of cavity tone using spanwise aligned jets, wind tunnel experiments and direct aeroacoustic simulations were performed to clarify the effects of the spanwise pitch of jets and mechanism of reduction of tone. As a result, the reduction level of sound pressure was clarified to be most intense at the jets of the pitch of $p/L = 0.25$ than $p/L = 0.1, 0.6, 1.25$. The computational results show that longitudinal vortices are induced in the upstream boundary layer at this pitch, while those are much weaker at the pitch of $p/L = 0.1$. These longitudinal vortices possibly inhibit the shedding of two-dimensional vortices in cavity flows, whose collision on the downstream wall cause acoustic waves.

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