Sound Suppression of Laminar Separating Flow over Cavity*

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A passive control of aerodynamic noise generated by a laminar separating flow over a cavity is carried out in a wind tunnel test and by numerical simulation, using a thin plate inserted into the cavity as a passive flow-controlling device. In the experiment, a noise suppression effect up to 14 dB is achieved by placing a plate in a proper location. It is shown that a plate of smaller vertical size is more effective. In the numerical simulation, it is shown that the location where the shear layer rolls up and the path of vortices are both very sensitive to plate position.

**Key Words:** Flow Control, Cavity Noise, Noise Suppression, Plate, Vortex

1. Introduction

Flow over an open cavity induces a strong and self-sustained oscillation, which generates an aeroacoustic sound, namely cavity noise. When a cavity is exposed to a flow, the separating shear layer rolls up into vortices, which consecutively hit the downstream edge. Periodical pressure fluctuation travels upstream and affects the formation of the shear layer, forming a feedback loop. Because of the feedback loop, aerodynamic noise from a cavity is generally a sound of large amplitude and single frequency. This problem is similar to the so-called Helmholtz resonator.

Cavity noise can be found in places such as buildings, automobiles with open sunroofs, landing gears on aircrafts and pipelines with closed side branches. This type of noise causes troubles as flow velocity increases. In particular, as for the high-speed train in Japan, aerodynamic noise is the major limiting factor of the maximum velocity. The strong sound pressures of cavity noise can also induce significant vibrations, which possibly destroy delicate instrumentation in the cavity.

In the last decade, a number of control techniques have been developed aimed at reducing cavity noise. Most of the methods tried to actively control the separating flow by introducing minute velocity fluctuations at the upstream edge of the cavity where the flow is most sensitive to disturbances. Kegerise et al.(1) used a flat actuator made from a piezoelectric bimorph cantilever beam. Cabell et al.(2) used a piezo-driven synthetic jet. Their actuators were activated by signals from a pair of pressure sensors located in the midplane of the floor and the rear cavity wall. Rowley and Williams(3) performed experiments to develop a model that can accurately predict the behaviors of different feedback controllers. They used a pair of loudspeakers in an enclosed chamber, which is activated with a feedback signal from pressure transducers located inside the cavity, to generate zero-net-mass blowing through a slot in the upstream wall of the cavity. Gloerfelt et al.(4, 5) investigated in detail the acoustic field of a flow over a cavity using a numerical approach.

Several attempts to reduce cavity noise by controlling the phase of the periodic flow patterns were carried out by our group using actuators attached on the upstream edge of the cavity. Yokokawa et al.(6)–(8) successfully suppressed noise by controlling the phase of each piezo-ceramic actuator along the spanwise direction. In addition to the active control, attempts to passively control the turbulent separating flow have also been made(9). A small and thin flat plate was inserted vertically into the cavity as a passive flow-controlling device. Compared with active control, a larger noise suppression effect was achieved although this effect was dependent on the location and size of the plate. It was also found that, the noise reduction effect became weaker in a large wind tunnel test. Because both wind tunnel experiments and numerical simulations are very difficult in this type of flows, the mechanism of how noise can be suppressed by a plate is still not clear.

In this paper, a passive control of aerodynamic noise generation is attempted against a laminar separating flow.
Both experimental and numerical attempts to control the flow and noise, using a thin plate inserted into the cavity are carried out. In a wind tunnel experiment, the effects of the size and location of the plate on noise suppression are investigated. A numerical simulation is carried out aimed at better understanding of mechanism of noise suppression.

2. Experimental Setup and Numerical Approach

2.1 Experimental method

The facility used in the experiment is a closed circuit, low-turbulence wind tunnel at the Institute of Fluid Science (IFS), Tohoku University. It has a nozzle with an octagonal cross section (293 mm from wall to wall). Figure 1 shows the model used in the experiment. The model is 900 mm long, 250 mm wide and has a rectangular cavity (streamwise length \(L_c=50\) mm, and depth \(=30\) mm) 300 mm downstream from the leading edge. To prevent flow separation at the leading edge, the model is mounted with -5 degree angle of attack in the open-type test section. The natural wavy pattern of velocity fluctuation in the cavity is two-dimensional so that two end plates are attached on both spanwise ends of the plate to maintain the flow conditions. The origin of the coordinate system is at the center of the upstream edge of the cavity, where the \(x\), \(y\), \(z\)-axes are in the streamwise, wall-normal, and spanwise directions, respectively. A flow controlling plate, which is 1 mm thick with various lengths \(H_p\) in the \(y\) direction, is placed inside the cavity as shown in Fig. 2. The plate is fixed on the floor by two L-shaped supports, where the top of the plate is as high as the upstream surface. A condenser microphone is used for the measurements of sound pressure level (SPL) given by

\[
\text{SPL} = 20 \log_{10} \sqrt{\frac{p^2}{p_0}}, \quad (1)
\]

where \(p\) is the pressure fluctuation and \(p_0 = 2.0 \times 10^5\) Pa is the reference pressure. To eliminate the near field effect, the microphone is set 900 mm above the center of the cavity, which corresponds to one and a half times the wavelength of the dominant frequency in this experiment. Single and X-type hot-wires are used to measure flow field. The signal from the hot-wire probes and the microphone are digitized by a 16-bit A/D converter and then processed by a computer running on Linux. At a uniform flow velocity of 18 m/s, the thickness of the boundary layer at the upstream edge of cavity is 2.5 mm, where the turbulence level of the free stream at the test section is about 0.1% of the uniform flow velocity.

2.2 Numerical method

To investigate the detailed mechanism of the noise controlling effect, a two-dimensional numerical simulation is also carried out. Incompressible Navier-Stokes equations are solved by a finite difference method. A third-order upwind (Kawamura-Kuwahara) scheme is used in the convection terms and a second-order central difference scheme is used for the other spatial differentiating terms. A fourth-order Runge-Kutta scheme is used for the time advancement.

The grid is shown in Fig. 3. It has 250×200 staggered grid points in the streamwise and wall-normal directions, where the grids shown in the figure are 1/3 and 1/4 of the total grids, respectively. The computational domain covers 50 mm in both the upstream and downstream directions from the ends of the cavity, and 30 mm above the cavity. The flow conditions are the same as those for the experiment. Blasius profile and Neumann condition are given as inlet and outlet conditions, respectively. The velocity gradient in the \(y\) direction at the top boundary is fixed at zero. A nonslip condition is imposed on the wall surface.

3. Results and Discussion

The SPL spectra of the cavity noise are shown in
Fig. 4. Peaks can be found at approximately 400 Hz, 800 Hz, 1 200 Hz and 1 600 Hz. By comparing with those in the cases with different freestream velocities, the peak near 400 Hz was found to be of fundamental frequency.

Figure 5 shows how the SPL spectrum changes with the streamwise position of the plate for the 5-mm-plate case. The dominant frequency peak of the noise shifts to a higher frequency of 600 Hz when the plate is placed upstream of the cavity (x/Lc = 0.1 ≃ 0.4). When the plate is set at x/Lc = 0.5, the strong peaks disappear and multiple peaks appear. Frequency differences between these new peaks are not the same, which indicates that two or more modes may coexist in the flow. For example, in the x/Lc = 0.9 case, the peak level at 800 Hz drops by 14 dB although the peaks at 1 200 Hz and 1 600 Hz continue to exist.

How the size and location of the plate affect the noise is shown in Fig. 6, where the vertical axis represents the difference in maximum peak level between the cases with and without control. From Fig. 6, it can be found that in all cases, the noise is suppressed when each plate is inserted around the middle of cavity. However, the noise increases when the plate is near the downstream edge, and when the vertical size of the plate (Hf) is large.

An X-type hotwire probe is used to determine how the flow field is changed by the insertion of the plate, whose size is Hf = 5 mm. The measurement is quite difficult since the mode of the noise is sensitive to an obstacle in the flow, and the hot-wire probe can be as an obstacle. An ensemble averaging technique is used to obtain the instantaneous velocity field synchronized to the fundamental and harmonic frequencies of the cavity noise. In this experiment, the sound signal was contaminated heavily by the background noise, so the reference signal had to be extracted by applying a band-pass filter to the original sound signal. Figure 7 shows the intensity map of the vorticity ωz inside the cavity when synchronized to the sound peaks near 400 Hz and 800 Hz for the no-control case. Although only one shear layer can be found in Fig. 7 (a), in Fig. 7 (b), two vortices can be found.

Figure 8 shows the pattern of vorticity fluctuation ωz for the cases with and without the plate. These fluctuation patterns are obtained by band-pass filtering for each frequency. Unfortunately, owing to the limitations of the probe configuration, the regions near the plate and the downstream edge of the cavity could not be measured. Figure 8 (a) and (c) appears quite similar to each other. On the other hand, when the plate is at x/Lc = 0.4 (Fig. 8 (b)), a strong vorticity fluctuation can be observed between the plate and the downstream edge of the cavity. By comparing Figs. 6 and 8, it was found that the strength of these vorticity fluctuation patterns inside the cavity is related to the SPL of the generated sound. For instance, in the Fig. 8 (b) case, cavity noise increases as shown in Fig. 6.
The results of the numerical simulation are shown in Fig. 9. The cavity flows with the plate which is installed at three different positions, \(x/L_c = 0.4, 0.5, \) and \(0.8\), are simulated. The no-control case is also shown in the figure. The size of the plate is fixed at \(H_p = 5\) mm. When there is no plate inside the cavity, the rolled-up vortices travel downstream and hit the downstream edge periodically (Fig. 9(a)). Almost the same patterns can be observed when the plate is placed at \(x/L_c = 0.8\), as shown in Fig. 9(d). However, in the latter case, oncoming vortices are distorted and stretched along the streamwise direction by the plate before reaching the downstream edge.

On the other hand, when the plate is placed near the leading edge at \(x/L_c=0.4\) (Fig. 9(b)), the location where the shear layer rolls up into vortices moves upstream. In this case, and a strong vorticity fluctuation can be observed inside the cavity. After a rolled-up vortex hits the plate, part of it forms a new and weaker vortex downstream. In Fig. 9(c), when the plate is at \(x/L_c=0.5\), the trajectories of the vortices regenerated at the plate appear to become more irregular. Some vortices pass over the downstream edge causing a separation of the flow at the downstream edge, while some hit the inner downstream wall of the cavity. It is also found that the flow behind the plate is strongly influenced not only by the timing the vortices hit the plate but also by the vortex motion inside the cavity in between the plate and the downstream edge. Generally, the flow is very sensitive to plate position.

Figure 10 shows an RMS profile of vorticity fluctuation for each case. When there is no plate in the cavity as shown in Fig. 10(a), the fluctuating area is limited within the narrow region along the shear layer. Almost the same pattern can be observed in Fig. 10(d), except for the region behind the plate near the downstream edge. On the other hand, when the plate is inserted at \(x/L_c = 0.4\) or \(0.5\), a footprint of the up-down movement of the shear layer can be found upstream of the plate. Similar distribution of \(\omega'_z\) appears from \(x/L_c = 0.1\) to 0.4 for the no-control case (Fig. 10(a)). However in cases (b) and (c), the high RMS region moves to a location right behind the upstream edge and it becomes stronger and thicker. This \(y\)-directional movement of the shear layer appears to influence the trajectory of the vortex regenerated at the plate, and vice versa. In each case, an area where the vorticity fluctuation is large can be found near the downstream wall (Fig. 10(b) and (c)), which indicates that the paths of the vortices are not constant and that the vortices approach the downstream wall at various locations. By comparing Fig. 10(b) and (c), it can be found that the flow pattern becomes quite different owing to a small change in plate location, \(x/L_c = 0.4\) and 0.5. Cavity noise derives from a self-sustained oscillation. The roll-up of the shear layer is influenced by the pressure wave caused by the periodical impingements of rolled-up vortices to the downstream corner, forming a feedback loop. The results of numerical
Fig. 9 Maps showing spanwise vorticities $\omega_z$ for (a) no-control case, (b) plate at $x/L_c=0.4$, (c) plate at $x/L_c=0.5$ and (d) $x/L_c=0.8$ cases (Numerical simulation)

Fig. 10 Maps showing RMSs of vorticity fluctuations $\omega'_z$ for (a) no-control case, (b) plate at $x/L_c=0.4$, (c) plate at $x/L_c=0.5$ and (d) $x/L_c=0.8$ cases (Numerical simulation)

Simulation show that the plate placed in the cavity plays two major roles. Plate weakens the feedback loop by directly weakening the vortices that hit the downstream corner, and by shaking the shear layer up and down preventing the vortices to hit the corner.

4. Conclusions

Experimental and numerical studies to control sound generation from a laminar separating cavity flow were carried out. In the experiment, a noise reduction up to 14 dB was achieved by inserting a thin plate into the cavity. The noise suppression effect was found to be very sensitive to the location of the plate. In some cases, noise increased with the placement of the plate. In the numerical study, it was found that the location where the shear layer rolls up and the paths of vortices were both very sensitive to plate position. A slight change in plate location could make a significant change in flow pattern, especially the paths of the vortices regenerated at the plate. This sensitivity of the flow to plate location must be the reason the noise suppression effect was very sensitive to plate location in the experiment.

References


