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Active Control of Aerodynamic Feedback Noise from a Small Step on a Backward-facing Step

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Abstract

In order to reduce an aerodynamic tonal noise from a rear-view mirror, active control technique with oscillating jets was utilized. Since the aerodynamic tonal noise of rear-view mirror was generated by a small perturbation caused by a small step on a surface of the rear-view mirror, oscillating jets were introduced to break it. Wind tunnel experiments were conducted to measure aerodynamic sound and flow fields around the two dimensional backward-facing step. The experimental results showed that the noise reduction level depended on the frequency and intensity of the oscillating jets. The noise reduction level was over 20 dB at the oscillation frequency about 400Hz and the amplitude of the jet about 0.1 m/s. Both of the frequency and intensity of the jet were smaller than the frequency of the feedback noise (2 kHz) and the velocity of the uniform flow (30 m/s). These results indicated that the oscillating jets effectively reduced aerodynamic noise with small amount of energy.

Introduction

Since the rear-view mirrors for automobiles made by combine two or more parts of the plastic construction, they have small steps or gaps in the surface. The progress of manufacturing process in automobile industries achieves to reduce the manufacturing error. Since the heights of the steps are low enough, steps was not recognized even if a customer touches the surface of rear-view mirror. The heights are usually less than 0.5 mm. However, the strong aerodynamic noise was generated by these small steps or gaps (hereafter, step and gap is called a "bump"). Kokubo *et al.* [1] experimentally showed that a strong aerodynamic noise was generated from a bump which height was only 0.3mm. In this paper, the noise which has a specific frequency defines as tonal noise. The noise level of tonal noise was 20 dB higher than that of broadband aerodynamic noise generated by the turbulent wake of a rear-view mirror. The experimental results showed the tonal noise seems to be aero-acoustic feedback noise.

Iida *et al.* [2] investigated the properties and the dominant parameters of this aero-acoustic feedback noise generation. The experimental results showed the noise level of the tonal noise depends on the boundary layer thickness and the condition of the approaching boundary layer. The noise level also depended on the distance from the bump to the edge of the rear-view mirror. The numerical simulation of the tonal noise was conducted with the unsteady compressible Naveir-Stokes equation [3]. The model of the aero-acoustic feedback of rear-view mirrors was established by using the numerical results, such as the relationship between vorticity and the acoustical field around the rear-view mirror. The frequency of the tonal noise can be predicted by using the model of the tonal noise generation.

These results indicated the seed of the tonal noise is small perturbation from a bump which has a sinusoidal fluctuation. This perturbation is small but it has the constant phase and coherent structure. Therefore, phase control of the small perturbation is effective way to reduce the tonal noise. The rounded edge of the rear-view mirrors reduced tonal noise. This is one of the passive controls of the tonal noise reduction. However, the flow around the rear-view mirror is related to the front shape of the automobiles or shape of A-pillar and so on. The thickness of the approaching boundary layer and the relative angle of attack of flow to the rear-view mirror depended on the environments of the cars. Therefore, there is a possibility that the control of the tonal noise is not suppressed only by a passive control that changes the shape of the door mirror (position of the bump and shape of the ridge line). It is difficult to predict flow conditions of the running cars and interactions of the car shape and flow around rear-view mirrors. Therefore the effects of the passive control may be limited in the real road situation.

In this investigation, we attempted to reduce the tonal noise with active flow control. To control or destroy the structure of the small perturbations, oscillating jets were impinging to the boundary layer of the rear-view mirror. The experimental results showed that the impinging jets effectively reduced the tonal noise. The level of tonal noise depended on the intensity of the oscillating jets. The remarkable result of this experiment that the required momentum of the oscillating jets to reduce the tonal noise was only 1/100 of the momentum of uniform flow. The noise level of the tonal noise depends on not only the momentum of the jet but also the frequency of oscillation.

Model of Tonal noise generation

Generally, when vortices pass a sharp edge, a strong aerodynamic noise is generated by the strong deformation of the vortices. The seed of tonal noise from the rear-view mirror is generated by this mechanism. First, small disturbances (vortex) introduced from the bump on the surface of the rear-view mirror, after that these disturbances generate strong aerodynamic noise at the edge of the rear-view mirror. The strong noise radiated from the noise source to the upstream excited the velocity fluctuations at the leading edge of the bump and then the excitation generated vortex shedding with the constant phase. Moreover, if the excitation for the vortex shedding and sound propagation is synchronized, flow field and acoustic field are resonant. As a result, the strong tonal-noise is generated from the small step.

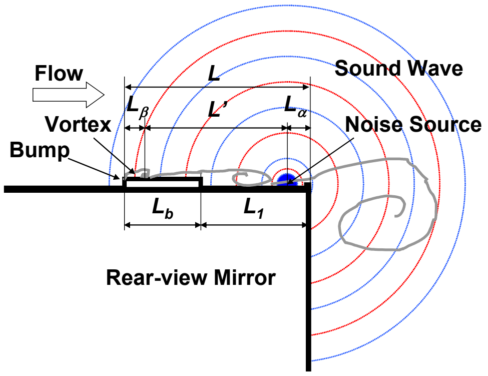


Figure 1 Schematics of rear-view mirror model

Figure 1 showed the schematic of the tonal noise generation of the rear-view mirrors. T_a denotes travelling-time of the sound from the noise source (near the sharp edge of the rear-view mirror) to the vortex source around a leading edge of the bump. T_v denotes travelling-time to the source of the vortex to the edge of the rear-view mirror; U_{cb} and U_c are convection velocity of the vortices on the bump and in the wake of the bump, respectively. The characteristic time of the feedback cycle can be formulated as follow;

$$T_a + T_v = \left(\frac{L'}{a-U}\right) + \left(\frac{L_b'}{U_{cb}} + \frac{L_1}{U_c}\right) \qquad (1)$$

Where a is a velocity of the sound wave, $L' = (L - L_\alpha - L_\beta)$ is a distance from the sound source (L_α) to the source of the vortex shedding around the leading edge (L_β).

Here, we used L_1 to calculate travelling time just behind the bump instead of the (L_1-L_α). Although the aerodynamic sound was generated at the L which is located at the upstream of the edge of the mirror, this phenomena was caused at the vortex interaction at the edge of the mirror. That is, the deformation of the small disturbance occurred at the edge of the mirror. The uniform velocity in the wake of mirrors is lower than the convection velocity of the small disturbances. The convection velocity therefore reduces rapidly near the edge of the mirror. As a result, the small disturbances are compressed and generated aerodynamic noise. Theerfore the characteristic length of the wave and vortices are not equal in the model of the tonal noise generation.

The resonance of the flow and acoustic field occurred when the characteristic time of (T_a + T_v) are equal to the time cycle of the small disturbances. An equation (2) shows the resonance condition of the tonal noise from a small bump on the surface of the rear-view mirror.

$$mT_m = \frac{L'}{a-U} + \frac{L_1}{U_c} + \frac{L'_b}{U_{cb}} \qquad (2)$$

Where T_m denotes the time cycle of the vortex shedding and the m denotes the number of the vortex in the feedback loop.

Equation (2) can be reduced as the resonant frequency of the tonal-noise. Here, non-dimensional frequency can be formulated as follows;

$$\frac{f_m L}{U} = \frac{m}{\dfrac{L'}{L}\dfrac{U}{a-U} + \dfrac{L_1}{L}\dfrac{U}{U_c} + \dfrac{L_b'}{L}\dfrac{U}{U_{cb}}} \qquad (3)$$

f_m is a resonant frequency of the tonal noise at modal numbers of m.

To calculate the equation (3), the convection velocities, the locations of sound and vortex sources are necessary. From the numerical simulation of aeroacoustic field with a compressible Navier-Stokes equation and the sub-grid scale model for turbulence for the flow around a rear-view mirror model [3], $U_{c\beta} = 0.29U$ and $U_c = 0.19U$ and L_α=3.5h and L_β= 5.0h are obtained. Here h denotes the height of the bump. The validations of the equation (3) were conducted with the wind tunnel experiments [2] and the aeroacoustic simulations [3]. Figure 2 showed the frequency of the tonal noise and estimated frequency by using equation (3).

Since the number of vortex cannot estimate without experiments or simulations, the modal number of m should be assumed. However, the predicted frequencies were in good agreement with the experimental results when the modal number of m was carefully chosen.

The results showed that the equation (3) was suitable to estimate the frequency of the tonal noise. It also indicated that the model of the tonal noise generation was suitable to explain the aerodynamic feedback noise of the rear-view mirrors.

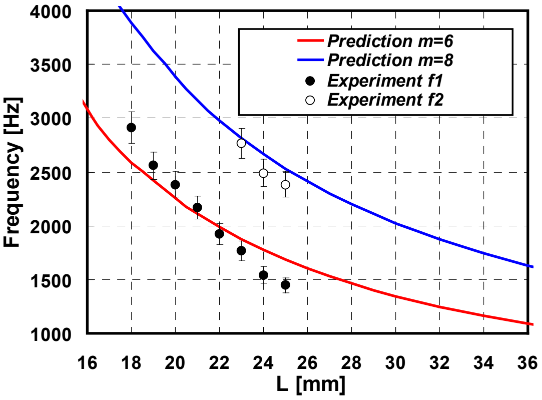


Figure 2 Mode frequency of tonal-noise

The model of the tonal noise generation as shown in Figure 1 indicated that the small disturbance played important role with tonal noise generation, it is thought that the control of the small disturbances seems to be the effective way to reduce the tonal noise. It is expected that the control of the small disturbances can be done with less energy. Since the energy of the sound is smaller than the kinetic energy of the uniform flow, the tonal noise can be controlled with small amount of energy compared to the drag reduction.

Experimental apparatus and experiment method

Aerodynamic noise and flow velocities were measured with a low-noise wind tunnel that has an open test section with a square cross section of 75mm by 150mm. This wind tunnel has an intensity of turbulence of less than 0.7 % and a non-uniformity of the velocity distribution about 0.1 % or less at a velocity of 30m/s. The background noise level of the wind tunnel is 64 dB at 30m/s.

The noise was measured at 550 mm from the bottom of the wind tunnel with a non-directivity microphone. The velocity of the flow was measured by a hot-wire anemometry with I typed single wire which diameter was 5μm. Flow visualizations were conducted by using a high-speed camera and a light source of infrared rays laser. The exposed time of the laser light was within the 5μsec. The frame rate was 5000 frames/minutes. The fog was introduced at the inlet of the wind tunnel to avoid the noise generation of the smoke-generator system. In order to understand the mechanism of the tonal noise generation, we attempted to visualize an instantaneous flow field around a bump by using this visualization system.

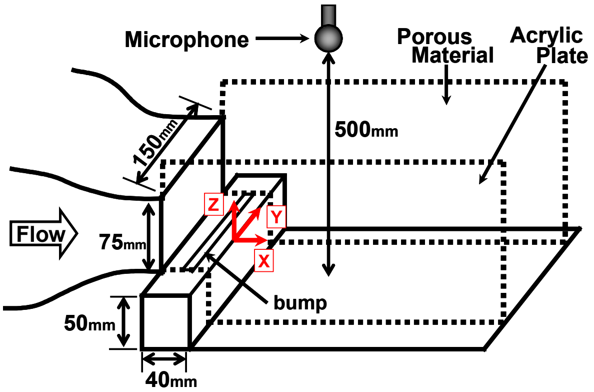


Figure 3 Schematics of wind tunnel setup and two-dimensional rear-view mirror model

The backward-facing step was installed the nozzle exit as a model of the rear-view mirror [5] as shown in Figure 3. The distance from the nozzle exit to the trailing-edge of the step is 40 mm and the height of the step is 50 mm.

The small bump was also fabricated on the surface of backward-facing step. The height of the bump was 0.7 mm which was about 40 % of the boundary layer and the bump was located at $L_1 = 11$ mm. The maximum level of the tonal noise was observed at above conditions.

To keep the two-dimensionality of the uniform flow, side walls were installed at the test section as shown in Figure 3. The one of the side wall is made by porous plate to avoid reflection and refraction of the sound. The test section was placed in an anechoic chamber.

Iida *et al.* [4] showed that the noise level of the feedback noise depended on the condition of the approaching boundary layer. When the approaching boundary layer was turbulent, the tonal noise was not generated. It seems to be constant phase and structure of the small disturbance which has a sinusoidal fluctuation was destroyed with random motion of the turbulence. As a result, the tonal noise was also reduced. Therefore the control of the small disturbances from the bump seems to be an effective way to reduce the tonal noise.

In order to control the small disturbance generated from the bump, the slit (width of 1 mm) was set in the centre of the bump for impinging jets exit. The oscillating jets were impinging by the speaker with resonance box as shown in Figure 4.

The input power of the speaker and the characteristic length of the resonator, Lr, controlled the intensity and frequency of the oscillation jets. The maximum frequency of the present experiments was 400 Hz and the experiments were conducted at the controlled frequencies from 150 to 400Hz at uniform velocity of 30 m/s.

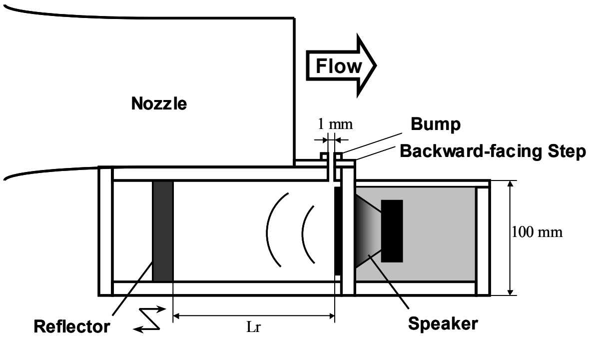


Figure 4 Schematics of test section and control unit

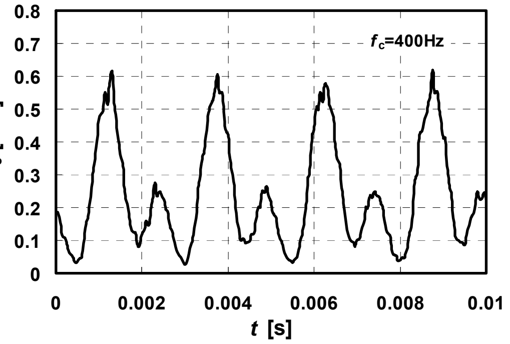


Figure 5 Time history of oscillating jet from a slit at wind velocity 0 m/s

Figure 5 shows the velocity of the impinging jet from the slit. The experiments were carried out at the uniform velocity of the wind tunnel was 0 m/s. The flow resistances of the outer-flow and in-flow at the slit were different; the velocity of the outer-flow and the in-flow were also different. In this paper, the characteristic velocity of the impinging jet defined as the average velocity of the one cycle of the oscillation. Figure 6 showed the characteristic velocity of the impinging jets. The velocity of U_e, depended on the frequency of the input signal of the speaker and the resonance length of L_r.

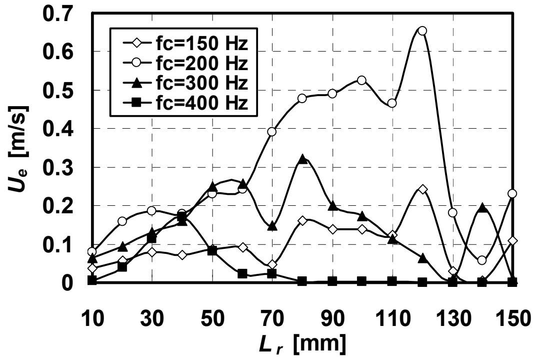
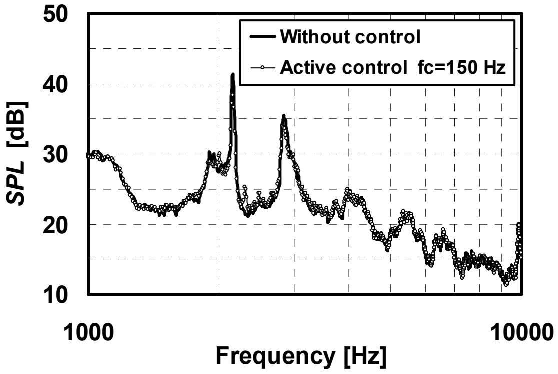


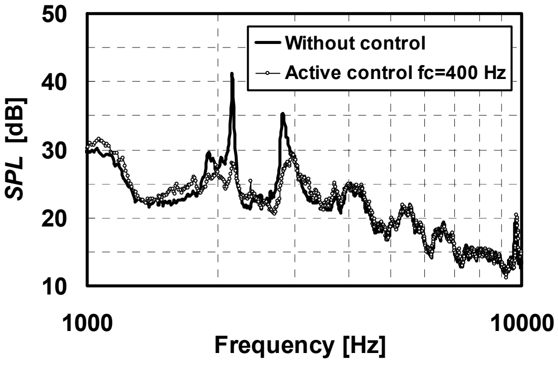
Figure 6 Relationship between the velocity and frequency of the oscillating jet at wind tunnel velocity of 0 m/s

Experimental results

Figure 7 shows the spectra of the aerodynamic noise radiated from the rear-view mirror model at the uniform velocity of 30 m/s. In the case of the control frequency was 150 Hz, noise reduction effect was hardly observed. On the other hand, the tonal noise can be reduced at the control frequency of 400 Hz, The noise reduction level was about 14dB. The control frequency was smaller than the frequency of the tonal noise (2200 Hz). The control frequency was 1/5 or less of the frequency of the tonal noise.



(a) f_c=150Hz



(b) f_c=150Hz

Figure 7 Comparison of sound spectra radiated from a real-view mirror model (U_o = 30m/s)

Figure 8 showed the relationship between the noise reduction effects and the control frequency. The ΔSPL denoted the difference between the radiated noise with and without the active control. In the experiments, the characteristic velocity of impinging jets of U_e, were constant at 0.03 m/s. The noise reduction levels were increasing with increasing the control frequency. The effect of the noise reduction of the tonal noise seems to be proportional to the control frequency.

Figure 9 showed effects of the noise reduction levels on the characteristic velocity of the active control. The experiments were done at the control frequencies from 150 to 400 Hz.

The noise reduction level was over 20 dB at the oscillation frequency about 400Hz at the amplitude of the oscillating jet velocity only 0.1 m/s. The uniform velocity around a rear-view mirror was 30 m/s. It indicated that the momentum or energy of the control jets were smaller than that of the uniform flow.

Figure 10 showed the flow field around a bump on the surface of the rear-view mirror. The separated boundary layer can be observed without the active flow control as shown in Figure 10 (a). The separated boundary layers reattached near the edge of the rear-view mirror. The separated boundary layer was also observed in the case of active flow control was adapted. The oscillating jets influenced the separated boundary layer. As a result, the flow fluctuations were introduced. Although the fluctuated flows generated the aerodynamic noise at the edge of the mirror, the fluctuated flows destroyed the sinusoidal disturbance around the edge of the back-step. And then, the phase of the turbulent noise seems to be not constant. Therefore, in this situation, tonal-noise was disappeared.

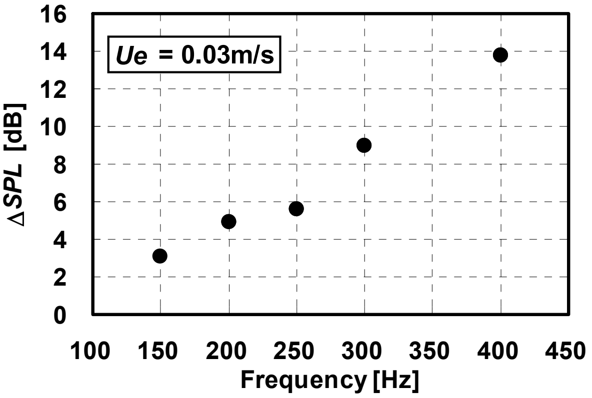


Figure 8 Dependence of the frequency of an active control on noise reduction level (U_o = 30m/s)

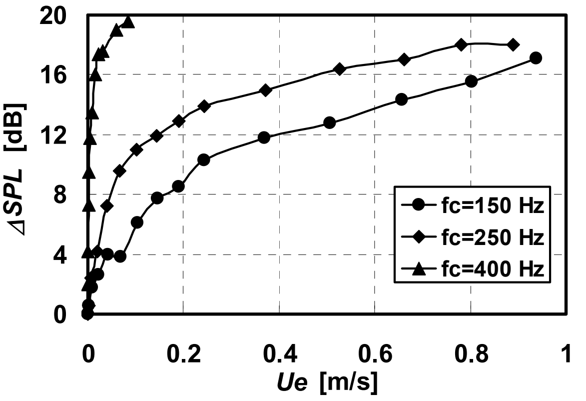
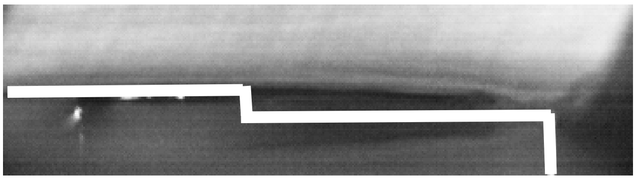
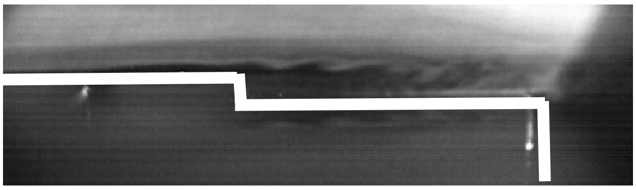


Figure 9 Dependence of intensity of control jet on noise reduction revel (U_o = 30m/s)



(a) Without active flow control



(b) With active flow control

Figure 10 Flow pattern around a bump on the back step (U_o = 30m/s)

Conclusion

In order to reduce the aerodynamic tonal noise from rear-view mirrors, active flow control was introduced and the experiments were carried out with the two-dimensional rear-view mirror model of the backward-facing step. The tonal noise radiated from rear-view mirror in commercial use was simulated by the small bump on the surface of the model.

Oscillating jets were generated by a speaker and the resonance box from a slit fabricated on the center of the bump. The tonal noise can be reduced by the oscillating jets. The noise reduction levels depended on not only the velocity of the oscillating jet but also the frequency of the oscillation. The control frequency was enough in 1/5 or less of the frequency of the tonal noise. The noise reduction level was over 20 dB at the oscillation frequency about 400Hz and the amplitude of the jet velocity about 0.1 m/s. It indicated that the energy or momentum of the noise control system was negligibly small compare to the energy or momentum of the uniform flows.

The experimental results revealed that the model of the tonal noise generation was reasonable and useful for considering the feedback mechanism of the tonal noise of the rear-view mirrors.

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